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PROCESSES AND DEVICES FOR CONTINUOUSLY MONITORING LEVELS OF  
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ABSTRACT:

The present invention provides a process and devices for continuously measuring the concentration of an analyte in tissue, which comprises providing said tissue with a hollow fiber having a pore size between the size of the analyte and the size of macromolecules, perfunding said hollow fiber with a solution compatible with the tissue, leading that solution from the hollow fiber through a reactor for the analyte, which reactor comprises a second hollow fiber having a pore size between the size of the analyte and the size of macromolecules, said hollow fiber being located in a container which comprises macromolecular reactants for detecting the analyte and a signal producing system coupled therewith, after which the perfusion fluid is lead from the reactor to an eliminator for the analyte, whereby at least 95% of the remaining analyte is removed from the perfusion fluid and reintroducing said perfusion fluid in said first hollow fiber. This is a closed circuit and therefore this method can be continued over a longer period of time than the methods of the prior art, without the need to replace reservoirs.

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(54) **Processes and devices for continuously monitoring levels of analyte.**

(57) The present invention provides a process and devices for continuously measuring the concentration of an analyte in tissue, which comprises providing said tissue with a hollow fiber having a pore size between the size of the analyte and the size of macromolecules, perfusing said hollow fiber with a solution compatible with the tissue, leading that solution from the hollow fiber through a reactor for the analyte, which reactor comprises a second hollow fiber having a pore size between the size of the analyte and the size of macromolecules, said hollow fiber being located in a container which comprises macromolecular reactants for detecting the analyte and a signal producing system coupled therewith, after which the perfusion fluid is lead from the reactor to an eliminator for the analyte, whereby at least 95% of the remaining analyte is removed from the perfusion fluid and reintroducing said perfusion fluid in said first hollow fiber.

This is a closed circuit and therefore this method can be continued over a longer period of time than the methods of the prior art, without the need to replace reservoirs.

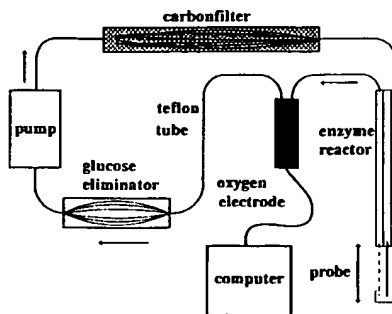


FIG. 2

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The invention relates to processes for continuously measuring the concentration of an analyte in tissue. It also relates to devices for said measurements and to devices which make such measurements and respond by administering an active substance.

In medical science, both human and veterinary, a very important criterion for diagnosis and or treatment is the level of certain substances in blood and/or tissue.

The substances of interest (hereinafter referred to as analytes) can be of a wide variety. They can be intermediates or endproducts in metabolism, hormones or hormoneprecursors, antibodies or antigens, pathogens, drugs, etc.

In a number of cases it will be important to keep a continuous check on levels of an analyte in blood and/or tissue.

The analyte which up until now has been the foremost subject in continuous measurements is glucose in patients suffering from diabetes mellitus.

Though the invention is explained more in detail using glucose as a model system, it is by no means restricted in its use to that kind of measurement only.

Processes and devices for continuously measuring glucose concentrations in (subcutaneous) tissue are known.

It has also been proposed to couple such a measuring device to a wearable insulin pump which then reacts to changes in the blood and/or tissue glucose level.

Generally speaking, these methods and devices are used for patients for whom the classical methods of injecting insulin once or twice a day cannot provide a satisfactory regulation of the glucose (blood) level in the patient.

However, if a patient friendly device for measuring analytes such as glucose and dosing a substance such as insulin in reaction to changes in the analyte concentration could be designed, the use of such devices could be far more widespread then this particular group of patients.

Several research groups are involved in designing glucose sensors. One of those research groups is the group of Shichiri of the "First Department of Medicine" at the university of Osaka, Japan. This group succeeded [see *Diabetologia* 24 (1983) 179-184; *Biomed. Biochim. Acta* 43 (1984), 561-568; *Diabetes Care* 9 (1986) 298-301] in developing a glucose sensor capable of measuring the glucose concentration in subcutaneous tissue for three days. The small needle-type glucose sensor consists of a platinum electrode covered with immobilized enzyme glucose oxidase. In the reaction of glucose with oxygen in the presence of the enzyme  $H_2O_2$  is released which can be measured by this electrode and correlates with the amount of glucose present.

In vitro the electrode gives a current of  $1.2 \pm 0.4$  nA in a 5.5 mmol/l glucose solution. The current is linear with the glucose concentrations, and the time required to obtain 90% of the plateau value is  $16.2 \pm 6.2$  sec.

In first instance, subcutaneous measurements were carried out in dogs, the response showing a delay of 5-15 minutes compared to the direct measurement in blood. The sensitivity of the electrode gradually decreases to  $57.4 \pm 7\%$  of the initial value after 96 hours measurement. This loss of signal, mainly due to the rapid breakdown of the enzyme, means that the subcutaneously inserted sensor must be replaced at least every three days.

Eventually, Shichiri developed a completely wearable artificial endocrine pancreas (12 x 15 x 6 cm, 400 g) consisting of the sensor, a microcomputer which calculates the required infusion rate of insulin, and a dual-syringe driving system. This apparatus is capable of controlling the blood glucose concentration in depancreatized dogs for three days. Shichiri then proceeded to measurement in subcutaneous tissue of diabetics. The subcutaneously measured glucose values are, on average, 10% lower than those of blood, but there is a good correlation between the two values in the range of from 60 to 400 mg/dl glucose. Then, patients suffering from diabetes were provided with the complete artificial pancreas, using a self-developed subcutaneous insulin infusion algorithm. Only one representative patient in which the glucose was controlled by the sensor for two days is mentioned.

Another research group is directed by M. Kessler of the institute for physiology and cardiology of the university of Erlangen-Nuremberg. The glucose sensor they developed [*Hepatogastroenterol.* 31 (1984)285-288] also operates through an enzymatic conversion of glucose by means of glucose oxidase, followed by measuring the resulting  $H_2O_2$  using an electrode with a gold anode covered with three membranes. A dialysis membrane permeable to glucose, gases and inorganic ions but impermeable to larger molecules, such as proteins, serves as a selector. In the next layer there is an enzyme membrane functioning as a kind of reaction space. Contained therein is the immobilized enzyme glucose oxidase. A sealing lipophilic membrane with incorporated proton carrier molecules is closest to the gold anode. In the presence of the enzyme the glucose diffusing through the dialysis membrane reacts with oxygen, thus forming  $H_2O_2$ . The

H<sub>2</sub>O<sub>2</sub> is oxidized at the gold anode so as to form two protons. These are eliminated by the proton carriers. With this sensor Kessler carried out measurements in the peritoneum of anesthetized rats. He found a good correlation between the glucose values measured in the peritoneum and the real blood glucose values. Dimensions of the electrode are not mentioned, but an electrode suitable for implantation in human beings is not yet available.

A. Müller and P. Abel of the Zentralinstitut für Diabetes "Gerhardt Katsch" from Karlsberg (GDR) (Prof. U. Fischer) also have a glucose oxidase/H<sub>2</sub>O<sub>2</sub> sensor available [Biomed. Biochim. Acta 43 (1984) 577-584; Biomed. Biochim. Acta 45 (1986) 769-777]. Again the immobilized enzyme is attached to the electrode (Pt) surface. The electrode is covered by respectively a hydrophobic and a hydrophilic membrane as a selector for the glucose. After an initial unstable period of 24 hours this electrode gives a stable signal, i.e. a current of 0.02-6.8 nA, depending on the glucose concentration. It is 7 cm in length and has a diameter of 2-4 mm. The electrode was implanted in 6 dogs and the glucose was measured. The ratio between glucose concentrations in blood and in tissue then varies from 33 to 70%. Besides this large variation, failures occur frequently so that a good calibration is not possible.

All the glucose sensors hitherto discussed that have already reached the experimental in vivo stage are based on a system with immobilized enzyme glucose oxidase on an electrode. This has the advantage that the electrode can be miniaturized and readily implanted in whole. However, an important drawback is that under those conditions the enzyme stability is limited and that consequently frequent replacement (3-4 days) of the electrode is necessary. Another requirement in the technique of immobilization is that each electrode must be calibrated individually and that it takes several hours to a day before the electrode can give a stable signal.

In European patent application No. 88908397.8 a device is disclosed which, like the devices of the invention does not use an implanted electrode, but uses an implant of a hollow fiber, which is suitable for microdialysis.

This device however, requires a reservoir of perfusion fluid and a reservoir for fluids which have passed through the hollow fiber. In other words it is not a closed circuit and both reservoirs need to be changed frequently.

The present invention provides a process and devices for continuously measuring the concentration of an analyte in tissue, which comprises providing said tissue with a hollow fiber having a pore size between the size of the analyte and the size of macromolecules, perfusing said hollow fiber with a solution compatible with the tissue, leading that solution from the hollow fiber through a reactor for the analyte, which reactor comprises a second hollow fiber having a pore size between the size of the analyte and the size of macromolecules, said hollow fiber being located in a container which comprises macromolecular reactants for detecting the analyte and a signal producing system coupled therewith, after which the perfusion fluid is lead from the reactor to an eliminator for the analyte, whereby at least 95% of the remaining analyte is removed from the perfusion fluid and reintroducing said perfusion fluid in said first hollow fiber.

This makes the sensing system a dynamic closed loop circuit and therefore this method can be continued over a longer period of time than the methods of the prior art, without the need to replace reservoirs.

To create a closed loop microdialysis based (glucose) sensor it is absolutely necessary to remove or eliminate all the analyte (glucose) (>95%) in the dialysate before re-entering the body microdialysis circulation to avoid accumulation of analyte (glucose) within the measuring circuit. Therefore an analyte (glucose) eliminating device, hereafter called glucose-eliminator (GE) has to be integrated within the dialysis circuit, either before or after the measurement cell.

Also very important is that the macromolecule (usually not of human origin) is not present in the perfusion fluid in any significant amounts. It has been shown that although the pore size of hollow fibers used in these methods reportedly is too small for such macromolecules that there will always be leakage of macromolecules. Therefore the device and/or method as disclosed in European patent application No. 88908397.8 would not be suitable for designing a closed circuit since the macromolecule would leak into the tissue and give rise to allergic reactions, inflammation and/or hypersensitivity for the macromolecules.

In the methods of the present invention the macromolecules are separated from the perfusion fluid by a second hollow fiber which is permeable for the analyte, but not for the macromolecules.

The perfusion fluid is separated from the tissue by a first hollow fiber. If any or both of the hollow fibers leak some macromolecules, then still the amount of macromolecules coming into contact with the tissue would probably be too small to lead to serious problems.

In order to exclude even that small risk of body reaction to the macromolecules, it is preferred that a filter for such macromolecules is present in the fluid circuit, a suitable filter in a number of cases (for

glucose oxidase for instance) is an active carbon filter.

In many instances the macromolecule used to react with and thereby detect the analyte can be an enzyme for which the analyte is a substrate. This is preferred because an enzyme can perform a multitude of conversions and therefore the capacity to detect analyte will be sufficient for a prolonged period of time.

- 5 When antibodies or other reagents are used, they usually will only bind a couple of analyte molecules per macromolecule and thus have a much more limited capacity. When analytes are to be detected which are only present in trace amounts, this may suffice for a long enough interval. In the case of glucose measurements an enzyme is preferred.

A suitable enzyme which uses glucose as a substrate is glucose oxidase.

- 10 Glucose and oxygen react under the influence of glucose oxidase (GOD) according to the following scheme. One can either measure the amount of oxygen remaining or the amount of H<sub>2</sub>O<sub>2</sub> produced.



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For measuring continuously in vivo this method has a few drawbacks:

- 1) The O<sub>2</sub> concentration in the fluid to be measured (saturated in water or body fluid) is not sufficient. At glucose concentrations of 100 mg/dl or more the O<sub>2</sub> concentration is already zero and glucose is no longer measurable. Therefore, the concentration of glucose participating in the enzymatic reaction should be restricted with respect to the O<sub>2</sub> concentration.
- 20 2) The enzyme GOD is degrading during the measurement, especially by the presence of hydrogen-peroxide, that is produced in the reaction.
- 3) H<sub>2</sub>O<sub>2</sub> diffuses easily into the body causing inflammation reactions. Even the enzyme GOD diffuses into the body by a few large pores that are inevitably present in the ultrafiltration membranes available at the moment.
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The use of a microdialysis system can prevent or circumvent the above mentioned problems:

- 1) A dilution of the glucose concentration in the body is easily achieved by selecting short hollow fibers in the probe or by adapting the perfusion rate.
- 2) An excess of enzyme, that may replace degraded enzyme, is easily introduced in the microdialysis system. For instance: a far higher concentration of dissolved enzyme may be applied, but also methods dosing the enzyme in a controlled way can be useful to extend the sensor lifetime significantly.
- 30 3) Diffusion of H<sub>2</sub>O<sub>2</sub> and/or enzyme into the body can be prevented by using the microdialysis system as an interface between the body and the measurement, in which the "hollow fiber" probe in the body is perfused only by a body compatible fluid.

- 35 It is preferred according to the invention to measure the used amount of oxygen, preferably using an electrode. This has the advantage that less stringent requirements need to be imposed on the quality of the enzyme employed. If the glucose sensor would be based on a measurement of the resultant amount of hydrogen peroxide, traces of the enzyme catalase which catalyzes the breakdown of hydrogen peroxide could adversely affect the accuracy of the measurement. A second problem associated with a measurement of the resultant amount of hydrogen peroxide is that the dialysis fluid containing the H<sub>2</sub>O<sub>2</sub> formed is to be immediately contacted with the electrode, resulting in that other substances in the dialysis fluid may have a disturbing effect on the measurement. This last-mentioned drawback could possibly be removed by using special membranes, e.g., specific cellulose ester membranes, but a perfect separation of dialysis fluid and electrode which only allows hydrogen peroxide to pass is hard to obtain. If, however, the used amount of oxygen is measured, the dialysis fluid can be perfectly kept separated from the electrode by means of a membrane which is only permeable to gases, such as a Teflon membrane, and the measurement can be carried out in a well defined electrolyte, such as a potassium phosphate buffer of 1/15 M K<sub>2</sub>HPO<sub>4</sub>.
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- In this connection it is preferred according to the invention that a measuring cell is used which comprises an operating electrode, an electrolyte space filled with electrolyte and a reference electrode, and the perfusion fluid is passed along the measuring cell via a flow chamber provided in a flow element, said flow chamber having an inlet for the perfusion fluid coming from the first hollow fiber and an outlet for the perfusion fluid to return to the first hollow fiber and being separated from the measuring cell by a membrane permeable to oxygen gas. As regards the measuring cell, it is preferred that an operating electrode of a noble metal, such as gold, silver and preferably platinum, and a reference electrode of silver are used, the electrolyte employed is a potassium phosphate buffer, preferably 1/15 M K<sub>2</sub>HPO<sub>4</sub>, the employed membrane permeable to oxygen gas is a hydrophobic membrane, preferably a Teflon membrane, and a voltage negative with respect to the reference electrode of about 0.6 V is applied to the operating electrode.
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Preferably the enzyme reactor, containing excess glucose oxidase and catalase, should convert all glucose present in the dialysate before passing the oxygen electrode (and function as the eliminator). In that case the measuring principle automatically prevents glucose accumulation. For reasons of increasing lag times and delay, however, the enzyme reactor is limited in size and probably will not be sufficient to  
 5 eliminate all glucose.

The reactor comprises a non-gas-permeable tube (for instance poly-ethylene: id 0.35 mm) through which a semipermeable membrane, preferably regenerated cellulose (od 200  $\mu$ m; MWCO = 9000 Dalton), is guided. Around the membrane the enzyme solution is located. Glucose diffuses from the interluminal space into the enzyme layer and is converted by the enzyme glucose oxidase. Resulting decrease in oxygen  
 10 concentration is reflected in the dialysate and is measured afterwards with the oxygen electrode. To guarantee a rapid measurement the diameter of the enzyme reactor should be as small as possible to promote rapid refelection of the decreased oxygen concentration into the interluminal space of the dialysis fiber.

A comparable design can be used as glucose eliminator to be integrated in the microdialysis circuit, preferably between the measuring cell (oxygen electrode) and the pump.

Glucose oxidase or any other enzyme converting glucose (for example glucose dehydrogenase) can be integrated in such an eliminator. Outer and inner diameters as well as type of the membranes used in such an eliminator are less important than in the enzyme reactor that is providing the measurement.

More cellulose membranes can be glued into an enzyme compartment to allow glucose to react within the eliminator. The enzyme solution should preferably contain catalase to eliminate the hydrogen peroxide, formed in the glucose oxidase reaction.  
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The enzyme based glucose eliminator can contain glucose oxidase and catalase in solution, but also other ways of enzyme immobilisation can be applied, such as fitting the enzyme in a gel or immobilize it on the inner wall of a tube. Contact time of the perfusion fluid with the enzyme (reactor) should be long enough to guarantee that all glucose is eliminated. Therefore dimensions of the glucose eliminator can vary widely in length and diameter.  
 25

A suitable glucose eliminator comprises a Teflon tube (id 0.96 mm, length 80 mm), through which four cellulose fibers are guided. Excess glucose oxidase and catalase ( $>40.000$  U/ml) are dissolved in saline (0.9% NaCl in water), surrounding the cellulose membranes. Since the eliminator is not meant to provide a measurement preferably oxygen permeable tubes are used for the construction, since sufficient oxygen is needed for the enzymatic reaction.  
 30

Other enzymes, like glucose dehydrogenase, can be used in the eliminator, provided that all cofactors and other reagents that are required are also present.

Other ways of eliminating glucose can be used to get rid of the glucose within the dialysate. Appliance of heat destruction by for example a glowing thread is a possible procedure, although energy consuming. Another way of consuming the dialysate glucose is the use of micro-organisms. Several types of micro-organisms are known to be selective consumers of sugars, so integration into a glucose eliminator could be possible. When aiming at in vivo appliance, though, additional safety measures should be made if micro-organisms are involved.  
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Another strategy to eliminate glucose within the microdialysis circuit is the use of specific chemical reagents to adsorb glucose or to react directly with glucose. Disadvantage of those type of elimination procedures is the fact that there will be a limit to their function. Adsorption capacity is limited and thus dependent on the amount of glucose which is present. The same counts for non-enzymatic chemical reactions. However, when an excess amount of a selective glucose eliminating chemical substance can be integrated within a device, such a design might be suitable.  
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The hollow fibers used for microdialysis must be permeable for the analyte (glucose).

Preferably a fiber of saponified cellulose ester having a molecular weight cut off value of about 10 kD is used. However, other types of materials are also useful, such as hollow fibers of polysulfone and acrylic copolymer (Amicon). The preferred cellulose fiber, however, is stronger and more flexible and can be inserted into the body more easily than the thicker and more vulnerable Amicon fiber.  
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As regards sizes, it is preferred that a hollow fiber is used having an inner diameter of 100-500  $\mu$ m, preferably 120-200  $\mu$ m, an outer diameter of 130-550  $\mu$ m, preferably 150-250  $\mu$ m, and being 0.1-3 cm, preferably 0.5-2.5 cm, in length.

Also, the nature of the tubes, leading to and from the first hollow fiber and otherwise present as connections between different elements of the devices, is not critical, provided they are airtight. Preferred are polyethylene tubes. As for their sizes, it is preferred that the airtight supply and discharge tubes have an inner diameter of 0.2-0.6 mm, preferably 0.25-0.35 mm, and an outer diameter of 0.4-1.0 mm, preferably 0.6-0.8 mm.  
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The length of the airtight discharge tube between the hollow fiber and the reactor must preferably be as small as possible so as to enable a rapid response. It is preferred that the airtight discharge tube between the hollow fiber and the reactor is 1-10 cm, preferably 1-5 cm, in length.

As regards the measuring element, it is preferred in connection with a high accuracy of the glucose sensor that a flow chamber is used having such sizes, shape and position of the perfusion fluid inlet and outlet that substantially no dead spaces occur. The exposed surface of the operating electrode which is separated from the perfusion fluid by the membrane permeable to oxygen (or to  $H_2O_2$ ) may be transverse to the direction of flow of the perfusion fluid or may also be in line with the perfusion fluid inlet opening, the distance between the inlet opening and the exposed surface of the operating electrode preferably being less than 5 mm, and most preferably less than 1 mm.

Further the invention provides an artificial pancreas, which comprises in addition to the devices already described, a regulable injection system for introducing active substances, such as insulin, into the organism; a calculating and regulating system for calculating the glucose concentration in the subcutaneous tissue on the basis of the measuring values of the measuring cell and a pertaining calibration curve, by means of an algorithm, the characteristic and relevant parameters of which are contained in a mathematical model, determining the amount of active substance to be supplied and controlling the regulable injection system in such a manner that the glucose (analyte) concentration in the tissue and/or in the blood remains within predetermined values. Preferably, the calculating unit also has an alarm function in case of extreme glucose concentrations in the body and in case of failures. The calculating unit can also have the secondary task of monitoring the curve of the memory concentration and insulin supply, storing same in the local memory and transporting same upon command of an external system to other data processing systems.

In the following the invention will be explained with reference to the accompanying drawings and by means of a description of conducted experiments.

## 25 Description of the figures.

Figure 1 represents a carbon filter which can be used in the methods and the devices according to the invention. The active carbon is present in a polyethylene tube provided with polyacrylonitrile fibers. At both ends the filter is connected with another element of the device through airtight polyethylene tubes.

Figure 2 gives a device according to the invention for measuring glucose levels, whereby the probe represents the hollow fiber to be implanted subcutaneously for microdialysis, said probe being connected to the rest of the device in a way that it can be easily disconnected and reconnected so that when the enzyme or the filter or the eliminator need to be replaced no reimplantation is necessary. In the figure the arrows give the flow direction of the perfusion fluid. Downstream from the probe, connected therewith through an airtight tube is the enzyme reactor, wherein the enzyme is separated from the perfusion fluid by a membrane permeable for glucose but not for glucoseoxidase. Downstream from the enzymereactor the oxygen produced in the reactor is measured by the oxygen electrode, which is electrically connected to a signal producing system outside the loop. From the electrode the perfusion fluid is lead through the glucose eliminator, which comprises a number of fibers through which the fluid is lead, which are permeable for glucose, but not for glucose oxidase. Surrounding those fibers is a chamber in which glucose oxidase is located. Downstream from the eliminator a pump is provided and downstream from the pump the carbon filter according to figure 1 is located. The perfusion fluid is lead from the filter to the probe.

Figure 3 and figure 3a give the output of a wearable device according to figure 2, when implanted in a healthy person. In the graphs the curve represents the glucose levels as measured by the device, the open squares are glucose levels measured in blood using standard methods. At the bottom of the graph the filled squares give the relevant events for the glucose levels. The measurements were continued with one device up until six days.

## EXAMPLES

### IN VITRO EXPERIMENTS

When the glucose sensor is used in vivo, it is of great importance that no Glucoseoxidase(GOD) enzyme molecules can diffuse into the body, because GOD can trigger an immuno-allergic reaction and give local irritation because of  $H_2O_2$  production. Even though the enzyme-solution is kept outside the perfusion fluid by means of a regenerated cellulose membrane, it is possible for some GOD molecules to enter the perfusion fluid. This is possible because each membrane has some so-called 'pin-holes', these are very large pores, through which GOD molecules can leak away into the perfusion fluid. By the

integration of a 'carbon-filter' in the flow system it's possible to remove the GOD molecules out of the perfusion fluid. Preferably this carbon-filter is placed between the pump and the dialysis probe. In this way the carbon filter is also dimming the pump pulse, thus creating a more constant perfusion flow.

The carbon-filter [fig 1] consists of a Polyethylene tube (id 3 mm, length 5 cm) into which a bundle of three Polyacrylonitrile fibers is placed. It is provided with approximately 50 mg of active carbon. Because of this extra filtration step, the perfusion fluid stays longer in the carbon-filter. This enables the carbon to adsorb the GOD molecules more effectively. The capacity of the carbon-filter can be increased by increasing the amount of carbon.

To determine how much GOD could be removed by the active carbon we performed the following experiments. To demonstrate the presence of GOD, we used Perid®-sticks impregnated with glucose. These sticks turn blue/green when GOD molecules are present in the test fluid. It is possible to detect a GOD enzyme concentration of 0.025 units GOD/ml.

Our first experiment was conducted to show that carbon indeed adsorbs GOD molecules. In this experiment we used carbon-filters as described above except for the bundle of Polyacrylonitrile fibers. We perfused these carbon-filters with a GOD solution of 30 units GOD/ml at a flowrate of 0.6 ml/hour. We tested the perfusate every hour on GOD molecules. After two and a half days the GOD molecules were found in the perfusate. We concluded that active carbon indeed adsorbs the GOD enzymes but the amount of adsorption depends on the concentration of active carbon and of the GOD concentration in the perfused GOD solution and the time that these GOD molecules are present in the carbon-filter.

In our second experiment we determined how many GOD units are adsorbed by a milligram of active carbon. Carbon-filters with a known amount of active carbon were perfused with a solution with a known concentration of GOD. No Polyacrylonitrile fibers were used in these filters. Every hour a sample was taken and checked for the presence of GOD molecules. The concentration of GOD adsorbed by one milligram of carbon was calculated. It appears that on average 1.8-0.2 units of GOD are adsorbed by 1 milligram of active carbon.

When the glucose sensor is used *in vivo* or *in vitro*, the perfusion fluid is regularly checked for GOD molecules. A perfusion sample is taken for and after passing the carbon-filter. In practice the carbon-filters are working very well for a period of at least a month; even when there are GOD molecules present in the sample before passing the carbon-filter, no GOD molecules were detected in the sample downstream of the filter. The durability of the carbon-filters can be increased by using a larger amount of carbon and the application of a bundle of polyacrylonitrile fibers. We have shown that in this way the purification of the perfusion fluid can be acquired and that the danger of GOD-leakage into the body can be prevented.

#### IN VIVO EXPERIMENTS

We performed with this new closed loop microdialysis system, 9 ambulant *in vivo* experiments on healthy volunteers in total. The mean duration of these *in vivo* trials was about 3 days. The longest *in vivo* experiment lasted for 6 days. These experiments were performed in such a way that the volunteers could go on with their daily life wearing the sensor system.

The glucose sensors [fig 2] used in these *in vivo* experiments were *in vitro* calibrated. The glucose concentration in the subcutaneous tissue is about  $45\% \pm 9$  of the blood value. With the data found in the *in vitro* calibration, the glucose concentration in the blood can be calculated at any moment.

The glucose probe of the glucose sensor is placed subcutaneously in the abdominal fatty tissue by means of a 16 Gauge catheter and fixated with a plaster. The boxes with the flowsystem and the portable data processor are worn in a belt around the subjects waist. The subjects were asked to measure their bloodsugar level regularly by means of commercially available wearable bloodsugar meter. These values give an indication of the subjects bloodsugar levels and are compared with the sensor measurements. The subject also notes what he or she eats and what he or she does, as far as relevant. These data are plotted in a graph to check the sensors' functioning. We never were confronted with an inflammation reaction at the sensor insertion side with one of the subjects.

#### Claims

1. A process for continuously measuring the concentration of an analyte in tissue, which comprises providing said tissue with a hollow fiber having a pore size between the size of the analyte and the size of macromolecules, perfusing said hollow fiber with a solution compatible with the tissue, leading that solution from the hollow fiber through a reactor for the analyte, which reactor comprises a second hollow fiber having a pore size between the size of the analyte and the size of macromolecules, said



hollow fiber being located in a container which comprises macromolecular reactants for detecting the analyte and a signal producing system coupled therewith, after which the perfusion fluid is lead from the reactor to an eliminator for the analyte, whereby at least 95% of the remaining analyte is removed from the perfusion fluid and reintroducing said perfusion fluid in said first hollow fiber.

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2. A process according to claim 1, whereby a filter is placed in the perfusion fluid stream between the reactor and the point of reintroduction of the fluid into the first hollow fiber.
3. A process according to claim 2, whereby the filter is an active carbon filter.
- 10
4. A process according to claim 1, 2 or 3, whereby the eliminator comprises an enzyme for which the analyte is a substrate.
5. A process according to claim 1, 2, 3 or 4, whereby the reactor comprises an enzyme for which the  
15 analyte is a substrate.
6. A process according to any one of the claims 1-5, whereby the analyte is glucose.
7. A process according to claim 6, whereby glucose is reacted with a glucose oxidase to produce a  
20 detectable signal.
8. A process according to claim 7, whereby the detectable signal used for detection is a decreasing amount of O<sub>2</sub> in the perfusion fluid.
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9. A process according to claim 8, whereby the decreasing amount of oxygen is measured with a measuring cell, comprising an operating electrode, an electrolyte space filled with electrolyte and a reference electrode, whereby the perfusion fluid is passed along the measuring cell, separated therefrom through an oxygen permeable membrane.
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10. A process according to claim 9, whereby an operating electrode of a noble metal and a reference electrode of silver are used.
11. A process according to any one of the claims 6 - 10, whereby the unreacted analyte is removed in the eliminator by reacting with glucose oxidase.
- 35
12. A process according to claim 11, whereby the eliminator comprises catalase.
13. A device comprising a fluid circuit for continuously measuring the concentration of an analyte in tissue, comprising:  
40 a hollow fiber having a pore size between the size of the analyte and the size of macromolecules, filled with a perfusion fluid which is compatible with the tissue, connected to a reactor, comprising a second hollow fiber, having a pore size between the size of the analyte and the size of macromolecules, which second hollow fiber is placed in a container, which container is provided with at least one macromolecular reactant for the analyte, said reactor in connection with  
45 a signal producing system, which detects one of the reaction products of the reaction between analyte and reactant and provides a signal,  
an eliminator for unreacted analyte, which is located downstream from the reactor,  
and a pumping means for circulating the perfusion fluid.
- 50
14. A device according to claim 13, whereby a filter is placed in the fluid circuit downstream from the reactor.
15. A device according to claim 14, whereby the filter is an active carbon filter.
- 55
16. A device according to claim 13 - 15, whereby the signal producing system comprises a noble metal operating electrode and a silver reference electrode in an electrolyte solution, which electrolyte solution is a potassium phosphate buffer, for measuring the decrease of oxygen in the perfusion fluid and which signal producing system is in contact with the perfusion fluid through a membrane permeable to

oxygen gas.

17. A device according to claim 13, 14, 15 or 16, whereby a macromolecular reactant is glucose oxidase and the analyte is glucose.
- 5 18. A device according to claim 17, whereby the signal producing system is coupled to a dosage instrument for administering glucose, which responds to the measured value of the signal.
- 10 19. A device according to claim 17 or 18, whereby the signal producing system is coupled to a dosage instrument for administering insulin, which responds to the measured value of the signal.
- 15 20. An artificial pancreas comprising a dosage instrument for administering glucose and a dosage instrument for administering insulin, both coupled to the signal producing system of a device according to claim 17.

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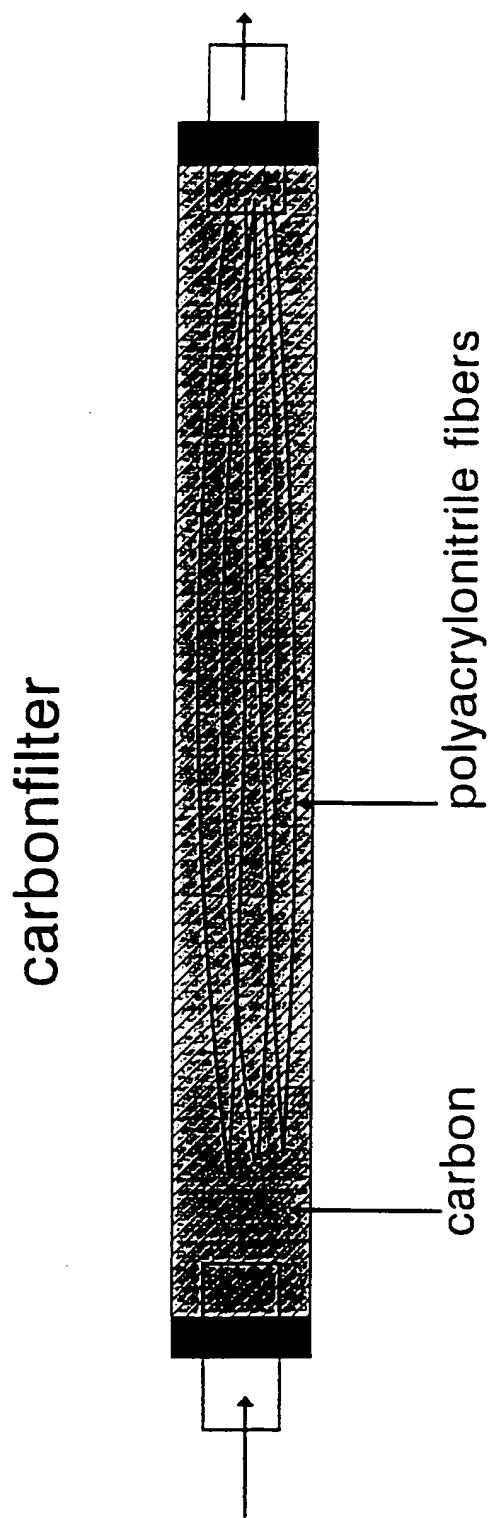


FIG.1

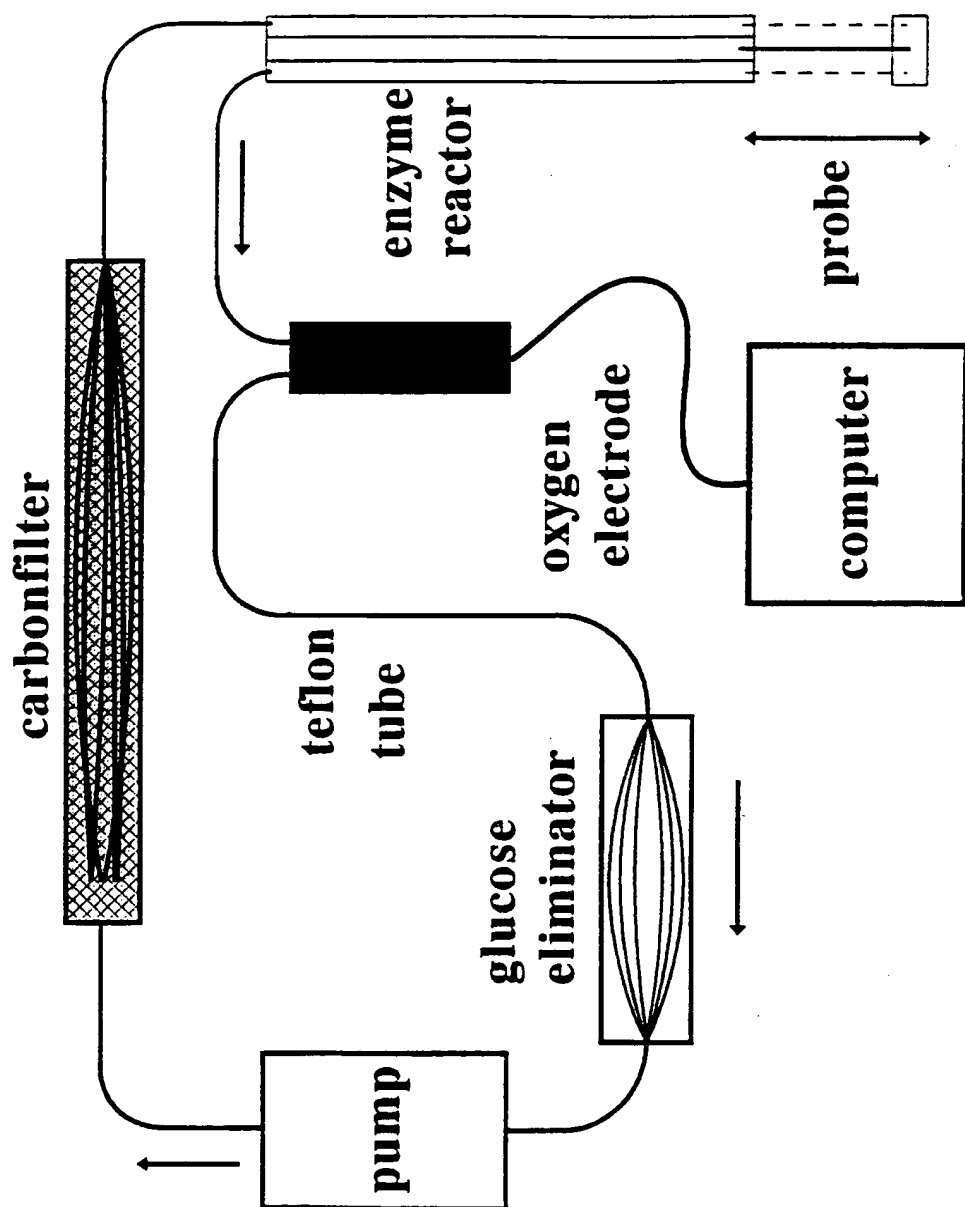
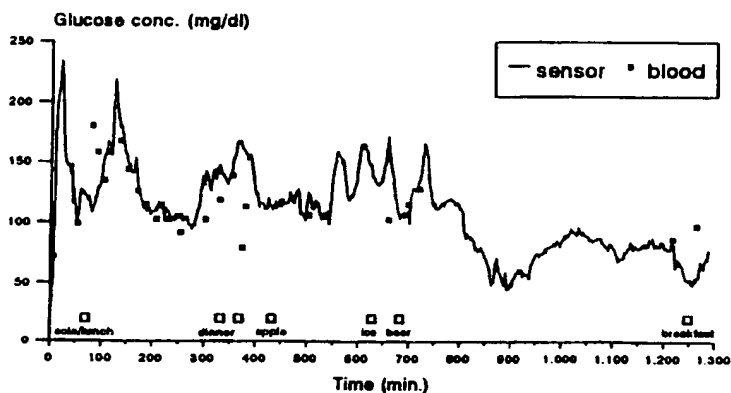


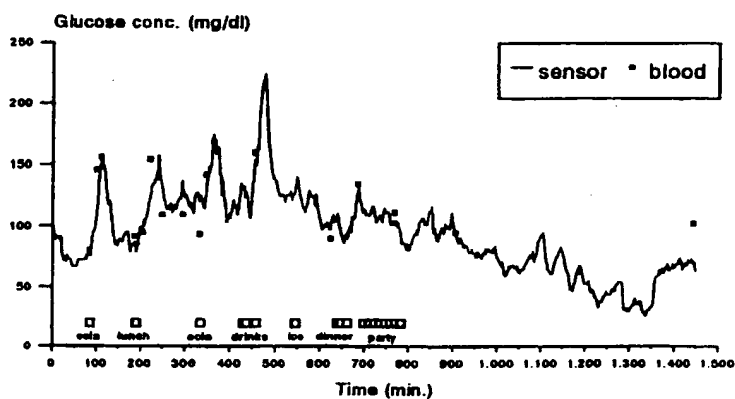
FIG. 2

Vivo A.W. 03-06-93  
(Day 1)



Calibration Factor : 0.85 Namp/mg/dl  
Temp. corr. Factor : 0.03 %  
Subcut. Glucose conc.: 45 % of blood Glucose conc.

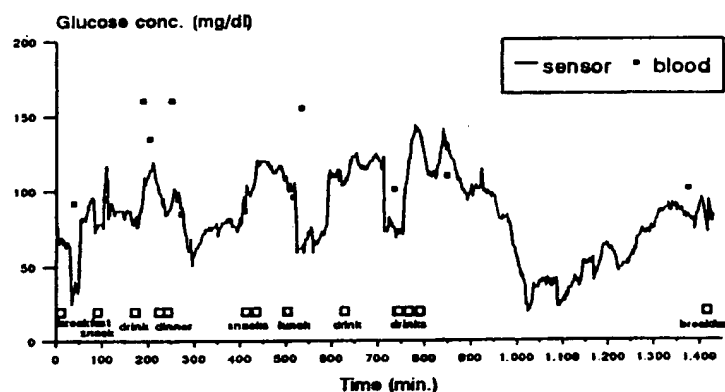
Vivo A.W. 04-06-93  
(Day 2)



Calibration Factor: 0.75 Namp/mg/dl  
Temp. corr. Factor: 0.03 %  
Subcut. Glucose conc.: 45 % Blood Glucose con.

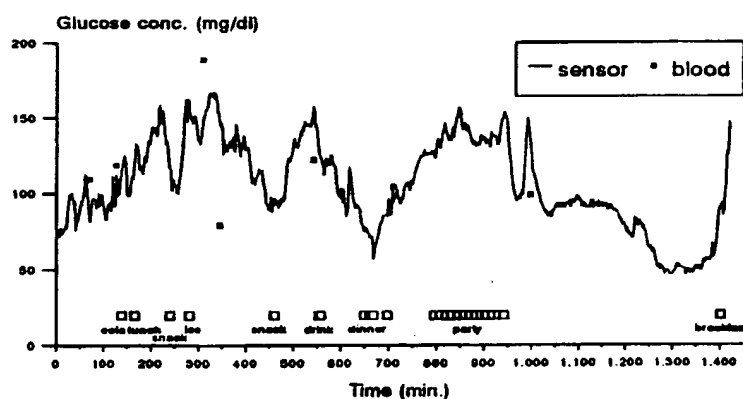
FIG. 3

Vivo A.W. 05-06-93  
(Day 3)



Calibration Factor: 0.75 Namp/mg/dl  
Temp. corr. Factor: 0.03 %  
Subcut. Glucose conc.: 45 % Blood Glucose conc.

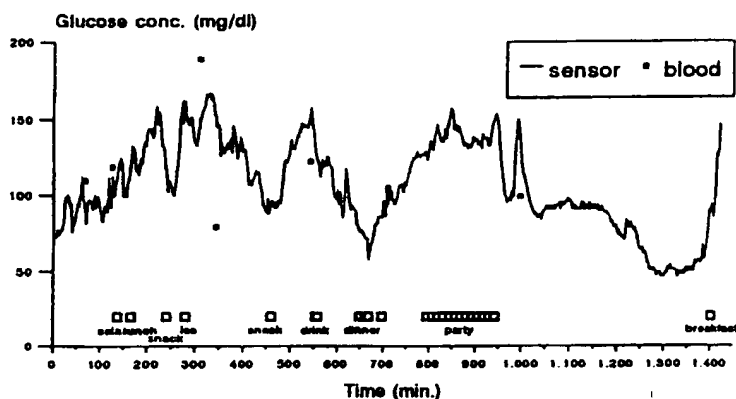
Vivo A.W. 06-06-93  
(Day 4)



Calibration Factor: 0.75 Namp/mg/dl  
Temp. corr. Factor: 0.03 %  
Subcut. Glucose conc.: 45 % Blood Glucose conc.

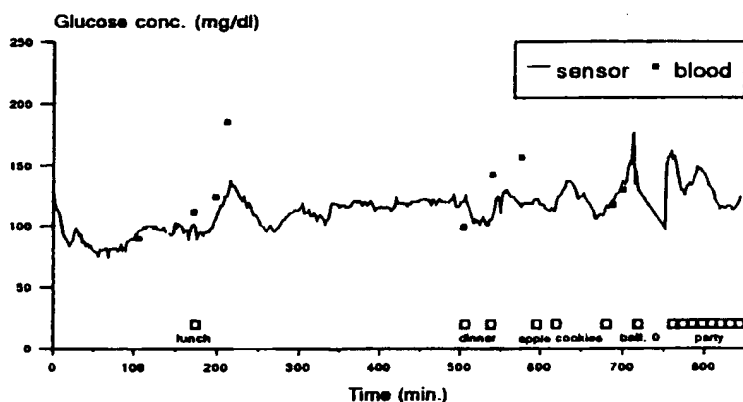
FIG. 3

Vivo A.W. 06-06-93  
(Day 4)



Calibration Factor: 0.75 Namp/mg/dl  
Temp. corr. Factor: 0.03 %  
Subcut. Glucose conc.: 45 % Blood Glucose conc.

Vivo A.W. 08-06-93  
(Day 6)



Calibration Factor: 0.75 Namp/mg/dl  
Temp. corr. Factor: 0.03 %  
Subcut. Glucose conc.: 45 % Blood Glucose conc.

FIG. 3a



European Patent  
Office

## EUROPEAN SEARCH REPORT

Application Number  
EP 93 20 2972

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
Y	EP-A-0 134 758 (G. BOMBARDIERI) * the whole document *	1,13,20	A61B5/00
A	---	5,6,18,19	
Y	US-A-4 247 647 (R.C. BARABINO ET AL.) * column 1, line 8 - line 12 * * column 2, line 24 - line 32 *	1,13,20	
A	---	4,11,12	
A	US-A-4 832 034 (V.B. PIZZICONI ET AL.) * the whole document *	1,4-7,13,17	
A,D	WO-A-89 02720 (STICHTING SCIENCE PARK GRONINGEN) * the whole document *	1,5-10,13,16-19	
A	US-A-4 192 748 (V.H. HYDEN) * the whole document *	1-3,13	
A	US-A-3 799 873 (C.E. BROWN) * the whole document *	1,13	TECHNICAL FIELDS SEARCHED (Int.Cl.6) A61B A61F A61M
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 25 February 1994	Examiner Ferrigno, A
<b>CATEGORY OF CITED DOCUMENTS</b> X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons * : member of the same patent family, corresponding document			